

An Enhanced Low Voltage Ride-Through Control Scheme for DFIG-Based Grid-Integrated Wind Energy Conversion Systems: Environmental Impact Analysis

P. Srinivasan^{1,*}, K. Arulvendhan²

^{1,2}Department of Electrical and Electronics Engineering, SRM Institute of Science and Technology, Ramapuram, Chennai, Tamil Nadu, India.
srinivasp808@gmail.com¹, arulvenk@srmist.edu.in²

Abstract: Over recent years, several nations have set up wind turbine generating systems (WTGS). Changing wind speeds, however, causes varying produced energy. Power generation and losses associated with wind turbine change concerning wind speed. Doubly Fed Induction Generator (DFIG) is the only machine that can produce power at constant speed. However, DFIG is oversensitive to grid faults, which leads to Bidirectional converters and DC-link capacitor failures due to high inrush current and over-voltage. Therefore, protection strategies should be adopted to prevent DFIG from faulting the grid. Voltage dips are very common in electric power systems, and one of the main events that get triggered during these dips is known as the Low voltage ride through (LVRT). To solve the above problem, eight protective measures have been used to avoid DFIG when voltage dips occur. In this paper, different techniques such as a blade pitch angle control, DC Chopper, crowbar circuit, series dynamic resistance, battery energy storage system, switch-type fault current limiter, Dynamic Voltage Restorer (DVR) FACTS Devices, reinforcement learning controller method, and machine Learning model are compared. This work investigates the hardware requirements and several control strategies with LVRT capability for wind energy conversion systems. Studied for symmetric and non-symmetrical fault circumstances, including torque, speed, and thermal stress.

Keywords: Doubly-Fed Induction Generator (DFIG); Low Voltage Ride Through (LVRT); Series Dynamic Resistance (SDR); Battery Energy Storage System (BESS); Switch-Type Fault Current Limiter (STFCL); Environmental Impact Analysis.

Received on: 26/03/2024, **Revised on:** 01/06/2024, **Accepted on:** 12/07/2024, **Published on:** 07/09/2024

Journal Homepage: <https://www.fmdbpublish.com/user/journals/details/FTSESS>

DOI: <https://doi.org/10.69888/FTSESS.2024.000302>

Cited by: P. Srinivasan and K. Arulvendhan, "An Enhanced Low Voltage Ride-Through Control Scheme for DFIG-Based Grid-Integrated Wind Energy Conversion Systems: Environmental Impact Analysis," *FMDB Transactions on Sustainable Environmental Sciences*, vol. 1, no. 3, pp. 161–172, 2024.

Copyright © 2024 P. Srinivasan and K. Arulvendhan, licensed to Fernando Martins De Bulhão (FMDB) Publishing Company. This is an open access article distributed under [CC BY-NC-SA 4.0](https://creativecommons.org/licenses/by-nc-sa/4.0/), which allows unlimited use, distribution, and reproduction in any medium with proper attribution.

1. Introduction

Ensuring the stable running of wind turbines during grid faults becomes a major issue as wind power is progressively entering the electrical system. Because of their variable speed control and great efficiency, doubly Fed Induction Generator (DFIG)--based wind turbines find extensive application. However, DFIG-based wind turbines are highly sensitive to grid disturbances, particularly voltage dips, which can lead to instability or even disconnection from the grid [1]. A Doubly Fed Induction Generator (DFIG) is widely used in Wind Energy Conversion Systems (WECS) due to its high efficiency, variable speed operation, and cost-effectiveness. The key feature of a DFIG-based system is that it allows independent control of active and

*Corresponding author.

reactive power by using a power electronic converter [2]. Unlike a squirrel cage induction generator (SCIG), which requires full-scale converters, a DFIG system only needs a partially rated converter (typically around 30% of the generator's rated power), making it more economical [3]. The power electronics system of a DFIG consists of a back-to-back converter structure, which includes two converters:

- Rotor Side Converter (RSC) – Connected to the rotor windings.
- Grid Side Converter (GSC) – Connected to the grid through a DC-link capacitor.

These converters enable efficient power conversion, bidirectional power flow, and grid compliance in variable-speed wind turbines. The back-to-back power converter system consists of:

1.1. Rotor Side Converter (RSC)

- Controls the rotor current to regulate active and reactive power.
- Implements vector control (Field-Oriented Control, FOC) to decouple torque and flux control.
- Mitigates effects of grid disturbances, such as voltage sags, using Low Voltage Ride-Through (LVRT) strategies.
- The RSC takes AC power from the rotor, converts it into DC, and then transfers it to the DC-link capacitor.
- It can control slip power to maintain generator operation in sub-synchronous and super-synchronous speed modes.
- A three-phase, two- or three-level IGBT-based Voltage Source Converter (VSC) is typically used.
- Uses Pulse Width Modulation (PWM) for smooth control.
- Contains protection circuits like crowbar circuits or braking resistors to handle grid faults.

1.2. DC-Link Capacitor

- Acts as an energy buffer between RSC and GSC.
- Maintains constant DC voltage despite variations in rotor speed and grid disturbances.
- The capacitor absorbs excess power when wind speed fluctuates, preventing converter overload.
- Helps in reducing harmonic distortion and stabilizing the voltage.
- Electrolytic capacitors for high energy storage.
- Film capacitors for better reliability and lower losses.

1.3. Grid Side Converter (GSC)

- Converts DC power from the DC-link capacitor into AC and injects it into the grid.
- Controls reactive power flow and maintains grid voltage stability.
- Helps ensure grid code compliance (e.g., fault ride-through capability).
- The GSC takes DC power from the DC link, converts it into three-phase AC, and synchronizes it with the grid voltage.
- It uses grid voltage-oriented control (VOC) to regulate power exchange between the generator and the grid.
- Usually, a three-phase, two-level, or three-level voltage source converter (VSC) with IGBTs is used.
- Uses sinusoidal PWM (SPWM) or Space Vector PWM (SVPWM) for efficient switching.

Low Voltage Ride-Through (LVRT) capability is crucial for grid-connected wind turbines, ensuring they remain connected and stable during voltage sag events. The traditional LVRT strategies rely on passive methods such as crowbar circuits, which protect the converter but reduce the controllability of the system. To overcome these limitations, an improved control strategy is proposed to enhance the LVRT capability of DFIG-based wind turbines while maintaining stability and grid compliance. In this fault, the terminal voltage across the grid is lower than the threshold value, and the stator current increases at this point, producing equivalent growth in the value of rotor current, which passes through RSC [4].

At this instant, RSC trips because of high inrush rotor current and DC-link capacitor trip due to over-voltage. The sag-withstanding capability of DFIG is under the influence of the Low Voltage Ride Through (LVRT) phenomenon [5]. The turbine must remain stable during the fault and can be reconnected to the grid with large voltage loss. The turbine is unsynchronised from the electricity grid when the voltage drops below the curve value [6]. The following are the few protection schemes to protect the converters from the above fault. A schematic diagram of a wind turbine based on DFIG is illustrated in (Figure 1).

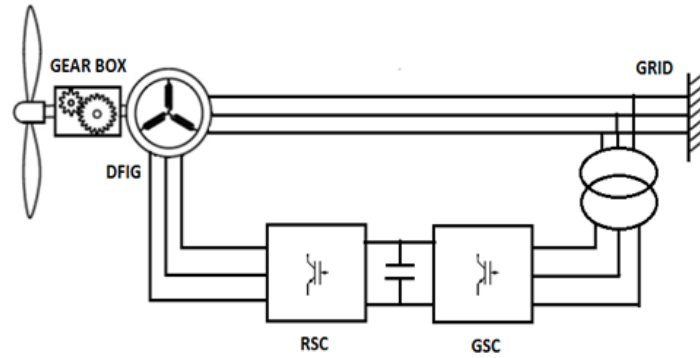


Figure 1: Configuration of DFIG based wind turbine

2. Grid-Code and Requirements

Wind turbines are set up in areas with sufficient wind power density and necessary provisions to land the production on the grid. But as winds grew more powerful, it became important to develop standard operating procedures. Such performance at wind turbine farms is because the wind turbine grid code indicates they should assist in controlling power as with any conventional systems, and thus, would remain connected when a fault occurs [7]. The important requirements include active power regulation and frequency control, voltage regulation ability, reactive power/power factor, terminal voltage limitations, supply frequency discrepancy limits, and FRT capability [8]. The grid code's main requirements are as follows:

2.1. Active Power

The generator used in wind turbines must be able to control active power; this will help inject a stable frequency and avoid overloading transmission lines with large steps up in voltages and rush currents during start and stop operations. When power is increased during faults, it should not cause large power surges.

2.2. Reactive Power

Wind power generating systems need reactive power support. Static capacitor banks or dynamic VAR devices like STATCOM are available to compensate for the reactive power requirement and to maintain the reactive power balance and power factor that needs static capacitor banks or dynamic VAR devices like STATCOM. The reactive power increases loss, overheating, and degrading of lines.

2.3. Frequency requirements

The supply frequency plays a major role in obtaining power balance in any system. An increase in demand leads to a fall in the frequency value; whenever demand decreases, frequency increases. Thus, the frequency varies from 49.5- 50.5 Hz due to the power imbalance. This occurrence can be rectified using primary and secondary control of the Conventional Synchronous Generator.

2.4. Low Voltage Ride-Through

The turbine keeps connected if the experienced voltage falls below the specified threshold value. Should voltage dip clear the fault naturally, the power generation from a wind turbine is unaffected. Disconnection of WT from the big wind farm results in more value of generation loss. For the given time, large wind farms should resist voltage sags for a few percentages (horizontal lines in indentral grid coding). Such limits are described in the FRT or LVRT capability requirement (Figure 2). presents a standard LVRT curve of voltage against time [9].

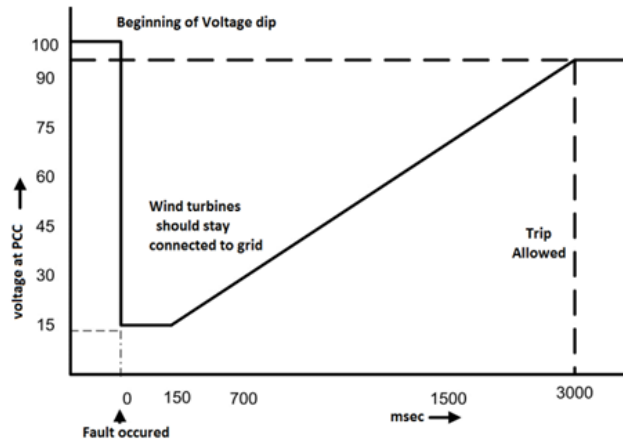


Figure 2: Typical LVRT curve

3. Review of Wind Turbine LVR Techniques based on Doubly Fed Induction Generators

LVRT capability improved in DFIGs using several methods discussed in this literature.

3.1. Blade pitch angle control

Pitch angle control refers to tuning the angle of movements of the rotor blades to control power production. The control system is adjusted to keep the blade pitch within the operating limits of change in wind speed. Compared with passive stall, pitch angle control captures more power from available wind speed. Based on the pitch control mechanism, wind turbines can be subdivided into fixed-pitch and variable-pitch. There are varieties of blades manufactured by different manufacturers. Variable pitch is required mainly for big machines to reduce aerodynamic loads and draw more power during fixed-speed operation. There should be proper maintenance, and for small machines, the fixed pitch is more suitable [10]-[12]

3.2. Crowbar methods

The crowbar protection circuit consists of three-phase diode rectifiers; the output of the rectifier is connected to a bypass resistor [13]. The passive crowbar circuit bypasses RSC using a crowbar resistor when DFIG is interrupted. However, the active crowbar circuit connects the crowbar braking resistor when essential and disconnects it to operate DFIG control without any disturbance that occurs to DFIG. In this work, the active crowbar circuit consists of a diode rectifier, whose output is linked to a crowbar braking resistor in series with an IGBT with on/off control for DFIG interruption, as shown in Figure 3.

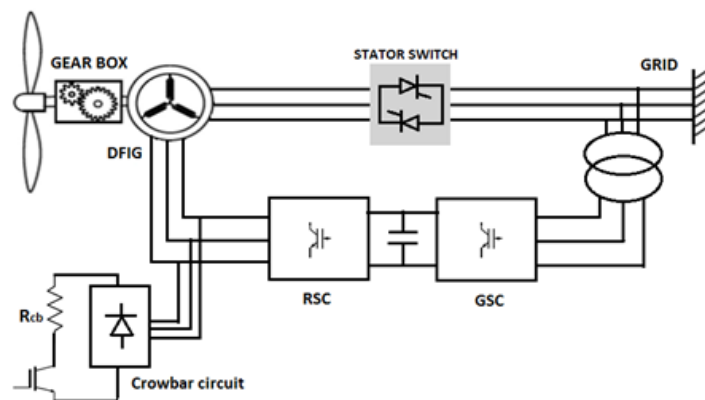


Figure 3: Crowbar Protection circuit

The brake resistor contacts DFIG whenever there is a drop in terminal voltage across the grid below the fixed value; the RSC is turned off as the crowbar is switched on. When the terminal voltage increases, the braking resistor disconnects from the DFIG rotor as the crowbar is switched off. The crowbar circuit connects the generator's rotor, preventing the power converter and improving LVRT capacity [14]. The Crowbar protection scheme's main advantage is preventing the converter and generator from being faulty. The primary drawback is that when a fault occurs, the crowbar circuit activates, and the DFIG loses control,

absorbing power from the grid and causing a further voltage drop [15]. The value of the braking resistor should be carefully calculated to minimize the losses and achieve adequate damping. To solve the abovementioned issues, a series of crowbar mechanisms is shown to the DFIG linked to the grid [16]. This system connects DFIG's stator to the grid using a bidirectional conduction switch (stator switch), so extra attention should be paid to lower the switching losses [17].

3.3. DC Chopper Protection Circuit

The DC Chopper protection circuit has a chopping resistor cascaded to a DC link capacitor. An IGBT is connected in series with a chopping resistor; depending on the rate of voltage across the DC link, the chopper may be turned on or turned off since the DC chopper is connected across a DC link, which protects the converter and dc-link capacitor from overvoltage during low voltage grid fault [18]. In Figure 4, the DC chopper circuit is displayed.

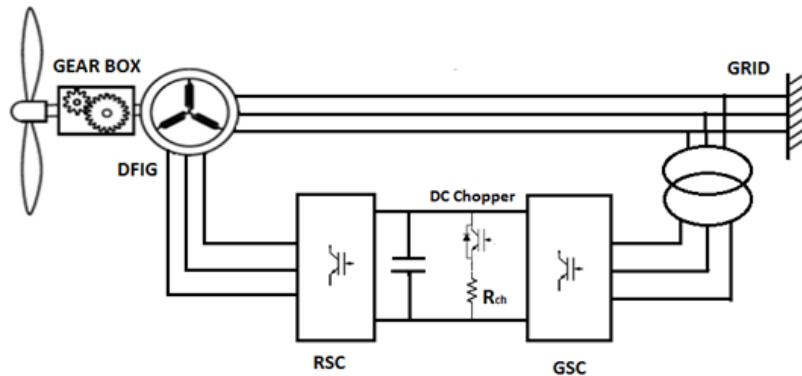


Figure 4: DC Chopper circuit

The DC chopper is activated whenever the voltage across the DC link rises, assisting in maintaining a stable voltage; the RSC is still connected to the DFIG rotor. When the voltage across the DC bus is lower than the preferred value, the DC chopper is turned off, and the DC chopper circuit prevents the converter and link capacitor during grid fault [19].

3.4. SDR Protection circuit

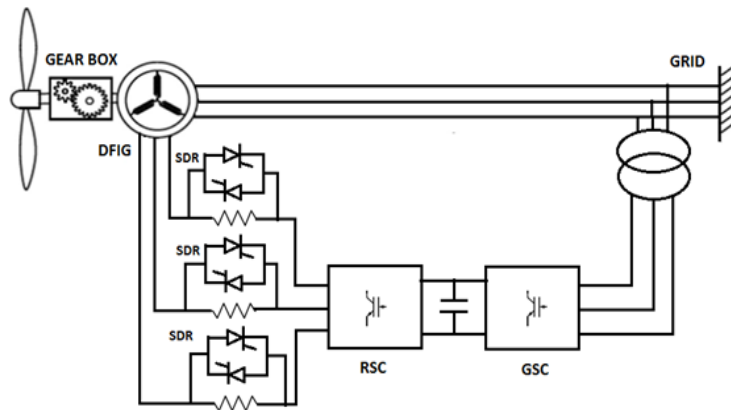


Figure 5: SDR Protection circuit

The series dynamic resistor is linked between the rotor of the DFIG and the RSC in this technique. The bidirectional switches connected across the SDR limit the over-current value entering the RSC during a fault condition; thus, the RSC is protected from over-current fault. Figure 5 features the SDR Protection Circuit. The normal terminal voltage across the grid lets the switches be in ON condition and passes a series of dynamic resistors, enabling the currents to enter RSC. When the terminal voltage falls below its rated value, the switches are turned off, and SDR is linked between the rotor of DFIG and RSC; the current entering RSC is limited. During various grid faults, SDR protects the converter from overvoltage and overcurrent. As a result, the voltage and charging current across the DC link capacitor are within safe limits. Crowbar and DC Chopper differ from SDR in that SDR is in series, whereas crowbar and DC Chopper are shunted.

3.5. Battery Energy Storage System

The goal of a battery storage energy system is to keep the voltage across a DC bus link constant. A DC-DC bidirectional converter connected to a DC link capacitor makes up this device. Figure 6 displays the battery-side converter control. During fault occurrence, the over-voltage across the link gets regulated and absorbed by the storage system, improving the LVRT capability. A bidirectional converter is connected between the DC bus and the energy storage system, which balances the power flow from the DC bus to BESS.

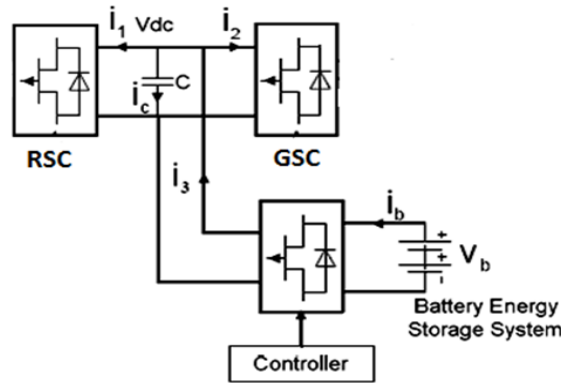


Figure 6: Battery energy storage systems

3.6. Switch-Type Fault Current Limiter

Switch-type fault current limiter (STFCL) uses fault-current limiting inductors (L_f) connected to the stator of DFIG to enhance LVRT capability. The static switch (S_d), snubber capacitor (C_f), isolation transformers, a diode bridge rectifier, a fault energy absorption bypass resistor connected in series to the capacitor, and fault-current limiting inductors make up the STFCL circuit (R_a and C_a). L_f is bypassed when the static switch (S_d) is turned on. Similarly, L_f is added to the DFIG stator when S_d is turned off. Snubber capacitor inhibit the transient overvoltage when S_d is in off condition. R_a limits the fault current entering C_a , and the fault energy absorption capacitor stores excessive energy supplied to the stator. STFCL protects DFIG from over current, overvoltage, and over torque and limits rotor back EMF voltage. Thus, it improves the RSC controllability and provides sufficient reactive power to the grid. The crowbar protection method passes the fault current through a bypass resistor, but in the case of STFCL, the fault current is reduced by using R_a and C_a . As a result, the STFCL technique of grid protection mitigates more serious grid concerns. The Switch-Type Fault Current Limiter Protection circuit is shown in Figure 7.

4. Based on reactive power injection

4.1. LVRT Techniques

Dynamic voltage restorer (DVR) and FACTS devices like STATCOM and UPFC are regularly used to introduce the reactive power during grid fault conditions to legitimately ride through low voltages, which are clarified as follows.

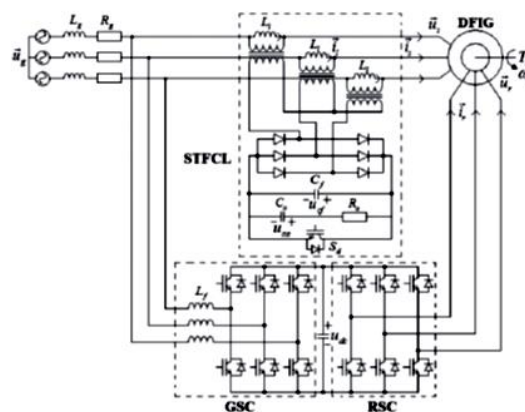


Figure 7: Switch-Type Fault Current Limiter

4.2. Dynamic Voltage Restorer

DVR is connected in series to the grid using coupling transformers to adjust for voltage sags and dips. The value of dips determines the converter's rating. This gadget optimizes the functionality of LVRT by acting as a series compensator. Likewise, the DC capacitor size should not surpass as much as possible to guarantee better LVRT performance for DFIG-based wind turbines. The DVR circuit is shown in Figure 8. However, they are typically not used in systems susceptible to voltage collapse and with persistent reactive power shortfalls (resulting in low voltage circumstances). A DVR-based arrangement is best suited for an LVRT enhancement solution in most conditions.

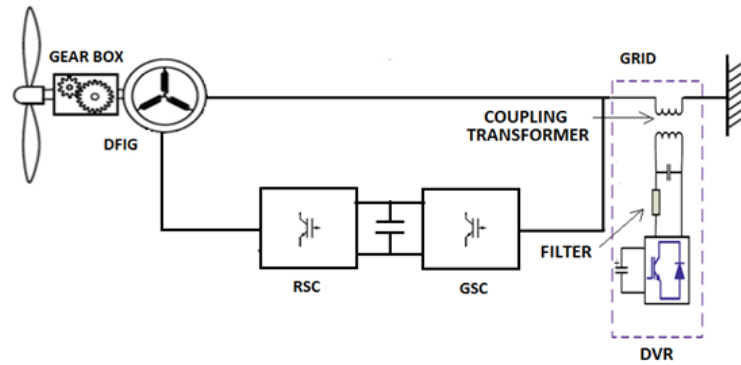


Figure 8: Switch-Type Fault Current Limiter

4.3. FACTS Devices

For better power exchange capability and stability, series and shunt-based FACTS compensation methods are used in power systems to improve power quality. FACTS-based devices like SVC and STATCOM work much better during LVRT enhancement. Under different grid fault conditions, LVRT-based Optimization of DFIG WTs is discussed. For superior LVRT improvement, Reactive power injection uses the unified power flow controller (UPFC).

4.4. Modified Vector Control Algorithms

Typical vector control of DFIG under steady state for GSC and RSC is as avowed, but its respective dynamic performance is worse. The modified vector control of DFIG is stated below. A virtual resistance system for rotor current-based LVRT improvement has been implemented. The Feed-forward transient current control (FFTCC) of RSC is discussed for personalized vector control. Emulating control using inductance is discussed. Finally, to achieve a better LVRT solution, the Virtual damping flux-based method is discussed.

5. Modelling of DFIG

DFIG modelling is shown in a synchronous (d-q) frame such that:

d-q reference frame voltage equations can be expressed as:

$$\begin{aligned} V_{qs} &= R_{si}q_s + P\Psi_{qs} + \omega_e\Psi_{ds} \\ V_{ds} &= R_{si}d_s + P\Psi_{ds} - \omega_e\Psi_{qs} \end{aligned}$$

Equation of rotor circuits in d-q frame expressed as:

$$\begin{aligned} V_{qr} &= R_{ri}qr + P\Psi_{qr} + (\omega_e - \omega_r) \Psi_{dr} \\ V_{dr} &= R_{ri}dr + P\Psi_{dr} - (\omega_e - \omega_r) \Psi_{qr} \end{aligned}$$

The present equation is articulated as:

$$\begin{aligned} i_{qs} &= 1/L_{is} (\Psi_{qs} - \Psi_{mq}) \\ i_{ds} &= 1/L_{is} (\Psi_{ds} - \Psi_{md}) \\ i_{dr} &= 1/L_{ir} (\Psi_{dr} - \Psi_{mq}) \\ i_{qr} &= 1/L_{ir} (\Psi_{qr} - \Psi_{md}) \end{aligned}$$

The equations for mutual flux linkage are provided as:

$$\Psi_{qm} = L_m (i_{qs} + i_{qr})$$

$$\Psi_{dm} = L_m (i_{ds} + i_{dr})$$

Flux Linkage expressions are represented as:

$$\Psi_{qs} = L_{siqs} + L_{miqr}$$

$$\Psi_{ds} = L_{sids} + L_{midr}$$

$$\Psi_{qr} = L_{riqr} + L_{miqs}$$

$$\Psi_{dr} = L_{ridr} + L_{midr}$$

The following equations help to premeditate the active and reactive power for both stator and rotor:

$$P_s = V_{ds} i_{ds} + V_{qs} i_{qs}$$

$$Q_s = V_{qs} i_{ds} - V_{ds} i_{qs}$$

$$P_r = V_{dr} i_{dr} + V_{qr} i_{qr}$$

$$Q_r = V_{qr} i_{dr} - V_{dr} i_{qr}$$

Where V_{ds} , V_{qs} , V_{dr} , V_{qr} , Ψ_{qs} , Ψ_{ds} , Ψ_{qr} , Ψ_{dr} , i_{ds} , i_{qs} , i_{dr} and i_{qr} stands for stator and rotor d axis and q axis voltage; successive ω_s , ω_r and ω_b the arbitrary, rotor and base rotating speed. Whereas successive ω_s , ω_r and ω_b the arbitrary, rotor and base rotating speed, V_{ds} , V_{qs} , V_{dr} , V_{qr} , i_{qs} , i_{ds} , i_{qr} , i_{dr} , i_{qs} , i_{dr} and i_{qr} stand for stator and rotor d axis and q axis voltage.

6. Performance of DFIG without any LVRT protection

The main goal of this work is to protect DFIG-based wind generators against short-circuit faults during LVRT. When symmetrical faults occur, the rotor circuit current rises to a higher value at the beginning and conclusion of the fault. However, compared to symmetrical faults, the winding stress of DFIG is higher. At the beginning of an unsymmetrical fault, the rotor current increases gradually, and finally, it becomes constant until the fault ends. Unsymmetrical faults cause greater thermal stress on the DFIG and converter winding than symmetrical faults do, and they also cause more torque and speed changes, which increases the mechanical stress on DFIG-based wind turbines without LVRT protection Tables 1 and 2.

Table 1: Hardware requirement to improve LVRT DFIG performance

No.	Solution
1.	Static switches for power conversion
2.	Rotor side series converter
3.	Supercapacitor as energy storage system to emphasize the DC link
4.	Nine-switch converters replace six-switch conventional grid-side converters.
5.	Arrangement of series and parallel GSC
6.	Implementation of SMES
7.	Supercapacitor energy storage system (SC)
8.	STATCOM connected with a capacitor energy storage system
9.	The stator is connected with an anti-parallel thyristor and IGBT for higher current-carrying capability.
10.	A protective arrangement consisting of an uncontrolled rectifier, two sets of IGBT an inductor, diode, and switch
11.	Superconducting fault current limiter (SFCL)

Table 2: Various control approaches to improve DFIG's LVRT

No.	Solution
1.	The control scheme activates the switch during the fault condition.
2.	Magnetizing current controller
3.	Effective resistance higher current limiter
4.	Genetic algorithm-based fuzzy controller
5.	Real and reactive power stream control using various references under fault and normal condition
6.	Effective resistance utilizing the RSC voltage
7.	A vector controller supports a non-optimal controller.
8.	Implementation of a controller for an unbalanced dip in voltage with regards to RSC and GSC

9.	A controller consisting of a bidirectional resonant-frequency compensator and a PI control device is used for imbalanced voltage circumstances.
10.	Momentary current controller based on feed-forward
11.	Controller for feedback linearization
12.	Storage of electrical power from kinetic energy wind turbine
13.	Internal hysteresis current control and exterior power-based control loop
14.	An adjustable oscillating controller
15.	Conversion of kinetic energy from waste energy
16.	Using two models to regulate the degree of flexibility
17.	Decentralized linear feedback controller
18.	Application of analogous soft torque synchronized control constant active power
19.	Control approach to track flux link
20.	Control approach to tracking phase angle
21.	A nebulous controller
22.	Non-optimal vector controller
23.	An indiscriminate controller for DC voltage controller
24.	Controller for unbalanced voltage drop
25.	Controller for second-order discontinuous control signal
26.	Direct form indication adaptive in-house controller
27.	Implementation of a control system that specifies numerous reference values for real and reactive powers in both stable and unsteady settings
28.	After an external short circuit, grid-powered WECS are re-established under stable conditions.
29.	For programming unreliable LVRT states, vibrant power control for dynamic control is employed.
30.	A controller to monitor DC link voltage
31.	A control method to consider dynamic magnetizing current in stator circuit
32.	A controller for nonlinear application
33.	Three individual current controllers utilized for symmetrical elements and quadratic linear regulator
34.	Implementation of stator magnetizing flux linkage in rotor current controller inference and DC composition

7. Machine learning-based optimization for LVRT enhancement

Through machine learning, computers can learn without explicit programming. As the name implies, it provides the computer with specific traits that allow it to learn more like a human. Data collection, data preparation, model selection, training, evaluation, hyperparameter adjustment, and prediction are the stages in machine learning. The neural network is used as the training model in this case, as shown in Figure 9. Artificial neural networks are based on biological principles. Because ANN comprises components that resemble real neurons, its anatomy may be comparable to the brain's. The data is collected at various wind speeds.

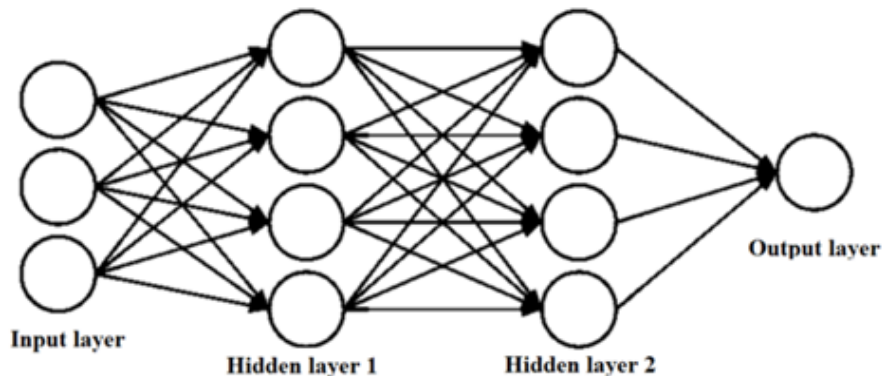


Figure 9: Model of a neural network

The inputs include wind speed, rotor currents, and rotor currents under faults. A network is taught to produce the intended set of outputs from a collection of inputs. Training is carried out by successively applying input vectors and adjusting network weights in line with a predefined method. During training, the network weights progressively achieve a value such that each input vector yields the desired output vector. Apply the input to the network input following the choice of the training pair from

the training set. Find the network's output. Find the variations between the target and the network output. As much modification of the network's weights as practical will help to reduce error. Repeat steps 1–4 for each vector in the training set until the error for the whole set is suitably low. Machine learning investigates and trains on various failure situations and rotor current variations.

8. Enhancement of LVRT capability using reinforcement learning controllers

Utilizing a convertible stationary compensator (CSC), the system employs a reinforcement learning methodology for controller design to increase a hybrid power system's low-voltage ride-through (LVRT) capacity.

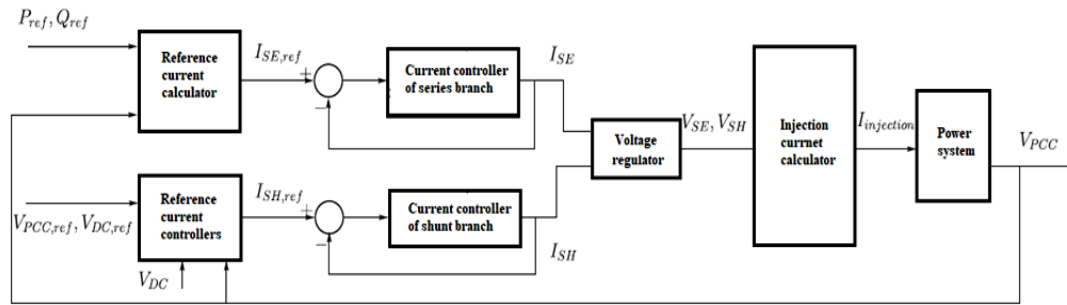


Figure 10: Reinforcement learning controllers in CSC

Using a Convertible Static Compensator (CSC), a Reinforcement Learning (RL) technique for controller design would create an adaptive control strategy capable of dynamically reacting to grid disturbances, hence improving Low-Voltage Ride-through (LVRT) capacity of a Hybrid Power System. A CSC is a flexible FACTS (Flexible AC Transmission System) device that can provide reactive power support, voltage regulation, and fault ride-through support.

8.1. RL-Based Controller Design

Instead of conventional PI controllers or droop control, an RL-based controller can learn optimal control policies from system interactions and RL Algorithm Selection:

- Deep Q-Network (DQN) – if the action space is discrete.
- Deep Deterministic Policy Gradient (DDPG) – for continuous control.
- Proximal Policy Optimization (PPO) – for robust policy learning.

8.2. State Space (Observations)

The RL agent observes real-time system parameters such as:

- Grid voltage (V)
- Reactive power (Q)
- Active power (P)
- CSC control signals (switching states, DC link voltage)
- Frequency deviation (Δf)
- Fault duration & severity

8.3. Action Space (Control Outputs)

The RL agent adjusts CSC parameters dynamically:

- Injection of reactive power (Q)
- Voltage compensation level
- CSC switching strategies
- Damping control settings

8.4. Reward Function

A well-defined reward function ensures the RL agent learns desirable behaviours:

$$R_t = -(W_1 \cdot |V_{ref} - V_{actual}| + W_2 \cdot |Q_{ref} - Q_{actual}| + W_3 \cdot \text{Overshoot})$$

Where:

w_1, w_2, w_3 are weights for different objectives. Penalty for excessive deviations in voltage, reactive power, or instability. Bonus rewards for quickly restoring voltage levels.

8.5. Training Process

- Simulation Environment Setup uses MATLAB/ Simulink, PSCAD, or Python (Open-AI Gym with Sim Power Systems) to simulate the hybrid power system. Model fault scenarios.
- Agent Training: Train the RL agent using off-policy algorithms (DQN, DDPG) or on-policy (PPO).
- Implement exploration-exploitation tradeoff (e.g., ϵ -greedy strategy for DQN).
- Use reward shaping to accelerate learning.
- Validation & Testing compare RL controller vs. traditional PI control.
- Evaluate response time, voltage recovery, and stability.

8.6. Expected Benefits of RL-Based CSC Controller

- Improved LVRT Performance: Faster voltage recovery.
- Self-Learning Capability: Adaptation to different fault scenarios.
- Optimized Reactive Power Control: Reduces grid stress.
- Minimized Overshoot & Oscillations: Smooth system response.

It has been shown that numerous FACTS devices, including SSSC, one STATCOM, two STATCOMs, UPFC, IPFC, and so forth, efficiently and effectively provide voltage support and power flow management. Though these elements have been studied, researchers have paid less attention to CSC's performance in enhancing voltage stability, small-signal stability, transient stability, transfer path stability of power systems, and their relevance in reaching LVRT. This work investigates whether reinforcement learning controllers combined with CSC may achieve LVRT capabilities in a hybrid power system, including both synchronous and asynchronous generators, including wind turbines. Figure 10 shows the hybrid power system concept whereby a reinforcement learning controller controls CSC. Whereas reference current in the shunt branch ($I_{(SH, ref)}$) is computed using the output of the planned reference current controllers, reference current in the series branch ($I_{(SE, ref)}$) is computed using reference current calculators. As shown in Figure 10, the injection currents are gathered from many different controllers, voltage regulators, and injection current calculators.

9. Conclusion and future work

For the wind turbine to comply with the grid code requirement, low voltage ride through (LVRT) is a crucial technique. There is a discussion of various LVRT protection solutions. This study examines and evaluates the techniques above. Since DFIG is oversensitive to grid voltage variations, few control techniques are implemented to prevent the bidirectional converter from disconnecting from the grid. The Crowbar protection method bypasses the fault current, but in the case of STFCL, the value of the fault current and rotor back EMF is limited. STFCL has excellent LVRT-enhancing capability when compared with the crowbar protection method. Different reinforcement learning-based controllers were used to control the CSC. Machine learning investigates and trains on various failure situations and rotor current variations. Advanced control strategies have also been discussed to improve LVRT performance. Future studies should be conducted on DFIG optimal performance to satisfy grid code constraints under several grid failures.

Acknowledgement: We sincerely thank SRM Institute of Science and Technology for their valuable support and encouragement. Their guidance and resources greatly contributed to the success of this work.

Data Availability Statement: Data is available upon request from the corresponding authors.

Funding Statement: This research received no financial support.

Conflicts of Interest Statement: No conflicts of interest were declared; all references were appropriately cited.

Ethics and Consent Statement: The research adhered to ethical guidelines, with informed consent and confidentiality ensured.

References

1. S. M. Mueeen, "Introduction," in *Wind Energy Conversion Systems*, Springer, London, United Kingdom, 2012.
2. R. Cardenas, R. Pena, S. Alepuz, and G. Asher, "Overview of control systems for the operation of DFIGs in wind energy applications," *IEEE Trans. Ind. Electron.*, vol. 60, no. 7, pp. 2776–2798, 2013.
3. H. T. Jadhav and R. Roy, "A comprehensive review on the grid integration of doubly fed induction generator," *Int. J. Electr. Power Energy Syst.*, vol. 49, no. 7, pp. 8–18, 2013.
4. I. Erlich, H. Wrede, and C. Feltes, "Dynamic behavior of DFIG-based wind turbines during grid faults," in *2007 Power Conversion Conference - Nagoya*, Japan, 2007.
5. A. Ahmad and R. Loganathan, "Development of LVRT and HVRT control strategy for DFIG based wind turbine system," in *2010 IEEE International Energy Conference*, Manama, Bahrain, 2010.
6. W. Sharad and M. V. Mohod, "Power quality and grid code issues in wind Energy Conversion Systems," *Energy engineering, An update on Power Quality*. INTECH, Rijeka, Croatia, 2013.
7. M. Tsili and S. Papathanassiou, "A review of grid code technical requirements for wind farms," *IET Renew. Power Gener.*, vol. 3, no. 3, pp. 308–332, 2009.
8. B. Singh and S. N. Singh, "Wind power interconnection into the power system: A review of grid code requirements," *Electr. J.*, vol. 22, no. 5, pp. 54–63, 2009.
9. B. S. Rajpurohit, S. N. Singh, and L. Wang, "Electric grid connection and system operational aspect of wind power generation," in *Wind Energy Conversion Systems*, Springer, London, United Kingdom, 2012.
10. M. Mohseni and S. M. Islam, "Review of international grid codes for wind power integration: Diversity, technology and a case for global standard," *Renew. Sustain. Energy Rev.*, vol. 16, no. 6, pp. 3876–3890, 2012.
11. F. Iov, A. D. Hansen, P. Sørensen, and N. A. Cutululis, "Mapping of grid faults and grid codes," *Risø National Laboratory*, Roskilde, Denmark, 2007.
12. H. Muhammad, D. Ph, and I. Fellow, *Fellow IEEE (USA), "Power Electronics Handbook devices, circuits and applications" Third edition*, Elsevier Inc, United Kingdom, 2011.
13. J. G. Sloopweg, H. Polinder, and W. L. Kling, "Dynamic modeling of a wind turbine with doubly fed induction generator," in *Proc. IEEE Power Eng. Soc. Summer Meeting*, IEEE, Vancouver, BC, Canada, 2001.
14. S. Seman, J. Niiranen, and A. Arkkio, "Ride-through analysis of doubly fed induction wind power generator under unsymmetrical network disturbance," *Power Systems*, *IEEE Transactions on*, vol. 21, no. 4, pp. 1782–1789, 2006.
15. C. Wessels and F. W. Fuchs, "Fault ride through of DFIG wind turbines during symmetrical voltage dip with crowbar or stator current feedback solution," in *2010 IEEE Energy Conversion Congress and Exposition*, Atlanta, Georgia, United States of America, 2010.
16. K. E. Okedu, S. M. Mueeen, R. Takahashi, and J. Tamura, "Wind farms fault ride through using DFIG with new protection scheme," *IEEE Trans. Sustain. Energy*, vol. 3, no. 2, pp. 242–254, 2012.
17. M. Ezzat, M. Benbouzid, S. M. Mueeen, and L. Harnefors, "Low-voltage ride-through techniques for DFIG-based wind turbines: state-of-the-art review and future trends," in *IECON 2013 - 39th Annual Conference of the IEEE Industrial Electronics Society*, Vienna, Austria, 2013.
18. I. Erlich, J. Kretschmann, J. Fortmann, S. Mueller-Engelhardt, and H. Wrede, "Modeling of wind turbines based on doubly-fed induction generators for power system stability studies," *IEEE Trans. Power Syst.*, vol. 22, no. 3, pp. 909–919, 2007.
19. S. Purushothaman, D. Samiappan, M. Kamalkannan, N. Joseph, and R. Murugavel, "LVRT enhancement of DFIG-based WECS using SVPWM-based inverter control," *Recent Adv. Electr. Electron. Eng. (Former. Recent Pat. Electr. Electron. Eng.)*, vol. 17, no. 4, pp. 345–357, 2024.